

# The Reanalysis of the *ROSAT* Data of GQ Mus (1983) Using White Dwarf Atmosphere Emission Models

Ş. Balman<sup>1\*</sup> and J. Krautter<sup>2</sup>

<sup>1</sup>*Department of Physics, Middle East Technical University, İnönü Bulvarı, Ankara, TR*

<sup>2</sup>*Landessternwarte, Königstuhl, D-69117 Heidelberg, Germany*

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## ABSTRACT

The analyses of X-ray emission from classical novae during the outburst stage have shown that the soft X-ray emission below 1 keV, which is thought to originate from the photosphere of the white dwarf, is inconsistent with the simple blackbody model of emission. Thus, *ROSAT* Position Sensitive Proportional Counter (*PSPC*) archival data of the classical novae GQ Mus 1983 (GQ Mus) have been reanalyzed in order to understand the spectral development in the X-ray wavelengths during the outburst stage. The X-ray spectra are fitted with the hot white dwarf atmosphere emission models developed for the remnants of classical novae near the Eddington luminosity. The post-outburst X-ray spectra of the remnant white dwarf is examined in the context of evolution on the Hertzsprung-Russell diagram using C-O enhanced atmosphere models. The data obtained in 1991 August (during the *ROSAT* All Sky Survey) indicate that the effective temperature is  $kT_e < 54$  eV ( $< 6.2 \times 10^5$  K). The 1992 February data show that the white dwarf had reached an effective temperature in the range  $38.3\text{--}43.3$  eV ( $4.4\text{--}5.1 \times 10^5$  K) with an unabsorbed X-ray flux (i.e.,  $\sim$  bolometric flux) between  $2.5 \times 10^{-9}$  and  $2.3 \times 10^{-10}$  erg s<sup>-1</sup> cm<sup>-2</sup>. We show that the H burning at the surface of the WD had most likely ceased at the time of the X-ray observations. Only the 1991 August data show evidence for ongoing H burning.

**Key words:** Stars: atmospheres – binaries: close – Stars: mass-loss – novae, cataclysmic variables – Stars: individual:(GQ Muscae) – X-rays: stars

## 1 INTRODUCTION

A classical nova outburst arises from the explosive ignition of accreted matter (i.e., thermonuclear runaway, TNR) in a cataclysmic binary system in which a Roche-lobe filling secondary is transferring hydrogen rich material via an accretion disk onto the white dwarf (WD) primary. During the outburst, the envelope of the WD expands to  $\sim 100 R_{\odot}$  and  $10^{-7}$  to  $10^{-3} M_{\odot}$  of material that reaches the escape velocity is expelled from the system (Starrfield 1989; Shara 1989; Livio 1994). The outburst stage usually lasts from a few months to several years and finally, the system returns to a quiescent state after outburst.

The TNR models with steady burning of H in an envelope on the WD surface have been successful in reproducing the typical nova characteristics in outburst (Starrfield Sparks, & Truran 1974; Starrfield et al. 1978; MacDonald 1983; MacDonald, Fujimoto & Truran 1985; Starrfield, Sparks, & Truran 1985; Prialnik 1986; Truran 1990; Starrfield et al. 1998 and references therein). According to these models, a gradual hardening of the stellar remnant spectrum with time past visual maximum is expected at constant bolometric luminosity and decreasing radius, as the envelope mass is consumed (i.e., via H burning and winds). As the stellar photosphere contracts, the effective (photospheric) temperature increases (up to values in the range  $1-10 \times 10^5$  K) and the peak of the stellar spectrum is shifted from visual to ultraviolet and finally to the 0.1-1.0 keV X-ray energy band (Ögelman, Krautter, & Beuermann 1987; Ögelman et al. 1993; MacDonald 1996; Balman, Krautter & Ögelman 1998 and references therein). The H burning continues at a constant rate and ceases when a critical mass in the envelope is reached below which stable hydrogen burning can no longer be established. The WD photosphere is expected to cool at constant radius. In addition to the photospheric component, the shocked nova ejecta can produce hard X-ray emission above 1.0 keV with X-ray temperatures  $\geq .1$  keV ( $> 10^6$  K) (O'Brien et al. 1994; Orio et al. 1996; Balman et al. 1998).

GQ Mus 1983 (GQ Mus) was discovered in outburst on 1983 January 18.14 UT (Liller & Overbeek 1983). It is also the first classical nova detected in the outburst stage by *EXOSAT* (Ögelman et al. 1984, 1987). The *EXOSAT* data was consistent either with an effective temperature  $\sim 25-30$  eV ( $3.0-3.5 \times 10^5$  K) and a luminosity of  $10^{37}-10^{38}$  erg s $^{-1}$  using a blackbody emission model or a shocked circumstellar material emitting  $\sim 1$  keV ( $10^7$  K) with a luminosity of  $10^{35}$  erg s $^{-1}$  using a thermal plasma emission model. GQ Mus was

\* solen@astroa.physics.metu.edu.tr

observed with the *ROSAT* *PSPC* on 1992 February 25-26 and was found to have an effective temperature of 30 eV ( $3.5 \times 10^5$  K) at near Eddington luminosity using a blackbody model of emission ( $L_E \sim 10^{38}$  erg s $^{-1}$  for 1 M $_{\odot}$  WD star) (Ögelman et al. 1993). This detection  $\sim 9$  years after the outburst was thought to be a confirmation of the anticipated constant bolometric luminosity phase of classical nova outbursts during which stable H burning occurs. The source was observed by *ROSAT* on three other occasions following 1992 February. At the time of the 1993 February 7-11 observation the temperature of the source was between 15 and 29 eV ( $1.7$ - $3.4 \times 10^5$  K) and only an upper limit of 21 eV ( $2.4 \times 10^5$  K) was derived using the 1993 September 3 data (Shanley et al. 1995). The source flux was unconstrained for all the observations of GQ Mus which may be attributed to the inappropriate model of emission used to analyze the X-ray data (i.e., blackbody). Such problems existed in the first analysis of the X-ray data of V1974 Cyg 1992 (V1974 Cyg) (Krautter et al. 1996) and the data was reanalyzed using metal enhanced LTE atmosphere emission models (Balman et al. 1998).

This paper will summarize a spectral reanalysis of the *ROSAT* *PSPC* archival data of the pointed and the RASS observations of GQ Mus, using better WD atmosphere emission models developed for H burning hot WDs in classical novae (MacDonald & Vennes 1991). We will discuss the implication of the derived spectral parameters on the standard novae theory and the characteristics of the WD.

## 2 THE OBSERVATIONS AND DATA

GQ Mus was observed on five different occasions with the *ROSAT* *PSPC* four of which were pointed observations; 1992 February 25-26, 1993 February 7-11, 1993 September 3, and 1994 July 6. The source was also detected during the RASS on 1991 August 5-6 with a count rate of  $0.143 \pm 0.035$  c s $^{-1}$  and a low S/N (Voges et al. 1999). The two other *ROSAT* *PSPC* archival data that are presented were obtained on 1992 March 24-25 (for V838 Her 1991) , 1993 May 1-2 (for V351 Pup 1991). The operational band of *ROSAT* *PSPC* is 0.1-2.4 keV and the energy resolution is  $(\Delta E/E) \sim 0.43$  at 0.93 keV (Pfeffermann & Briel 1986). The angular resolution of *PSPC* is 25'' for on-axis observations. In the analysis, the data were corrected for vignetting and dead time. The source and background count rates were derived using extraction radii in a range 105''–150''. The first 10 channels were excluded from the analysis due to low statistics and poor calibration. Table 1 displays important characteristics, count rates (derived in this analysis), and observation durations of the sources discussed in this

**Table 1.** The Count Rates For *ROSAT PSPC* Pointings Of Detected Galactic Classical Nova And Important Source Characteristics \*

Nova & Outburst year	E(B-V)	Distance (kpc)	$t_3$ <sup>1</sup> (days)	Time After Outburst (days)	Count Rate (c s <sup>-1</sup> )	Exposure Time (s)
GQ Mus 83 (RASS) <sup>2</sup>	0.45±0.15 <sup>3</sup>	4.7±1.5 <sup>4</sup>	40 <sup>3</sup>	3118 (8.5 yrs)	0.143±0.035	150
GQ Mus 83 (Pointed)				3322 (9.1 yrs)	0.127±0.006	5848
				3641 (10 yrs)	0.007±0.002	4296
				3871 (10.6 yrs)	<0.003	10091
				4190 (11.5 yrs)	<0.0015	3600
QU Vul 84	0.5-0.6 <sup>5</sup>	3.5±1.5 <sup>6</sup>	34 <sup>4</sup>	2340 (6.4 yrs)	0.003±0.002	10882
V838 Her 91	0.5 <sup>7</sup>	2.8-5.0 <sup>7</sup>	5 <sup>5</sup>	5	0.16±0.01	1235
				365	0.005±0.002	4425
V351 Pup 91	0.3±0.1 <sup>8</sup>	4.7±0.6 <sup>8</sup>	40 <sup>8</sup>	480	0.22±0.01	9554

(\*) V1974 Cyg 92 is excluded. (see Krautter et al. 1996) (1) Time it takes for the nova to decline three magnitudes. (2) Voges et al. 1999 (3) Krautter et al. 1984 (4) Ögelman et al. 1987 (5) Andrillat 1985 (6) Saizar et al. 1992 (7) O'Brien et al. 1994 (8) Orio et al. 1996

paper. The X-ray data were analyzed using EXSAS/MIDAS software package (Zimmermann et al. 1994).

### 3 ANALYSIS OF THE GQ MUS DATA WITH THE WD ATMOSPHERE MODELS

#### 3.1 The WD atmosphere models

The multiwavelength analyses of classical novae have shown that the ejecta are enhanced in CNO nuclei compared with the sun and some also show significant enhancement of Ne, Mg and heavier elements indicating existence of a Ne-O WD. The enhancement is generally believed to result from mixing between the WD core material and the accreted envelope prior to outburst (Iben & Tutukov 1995; Glasner, Livne & Truran 1997; Starrfield et al. 1998). As a result of the change in the opacity within the stellar remnant envelope due to mixing, the emergent stellar remnant spectrum is expected to differ from a simple blackbody model of emission. A hot WD spectrum would also show deviations from a simple blackbody spectrum (Heise, van Teeseling & Kahabka 1994). Thus, we developed a routine to analyze the soft X-ray spectra of classical novae using a set of model atmosphere continua provided by MacDonald (1994, private communication). The models are hydrostatic LTE atmospheres for a 1.2 M<sub>⊙</sub> WD at 11 different effective temperatures ranging from 1–10×10<sup>5</sup> K. They comprise two representative compositions: a C-O enhanced atmosphere with C/C<sub>⊙</sub> ~ 15, O/O<sub>⊙</sub> ~ 15 and Ne/Ne<sub>⊙</sub> ~ 7; an O-Ne enhanced atmosphere with C/C<sub>⊙</sub> ~ 1.2, O/O<sub>⊙</sub> ~ 14 and Ne/Ne<sub>⊙</sub> ~ 81 (MacDonald & Vennes 1991). In addition, H, He and N are also

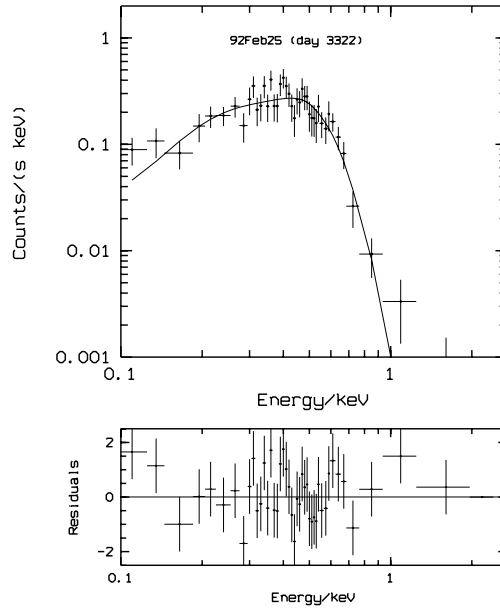
included in the models with  $N$  substantially greater than solar. Other details on the models and comparison with blackbody models of emission can be found in MacDonald & Vennes (1991). The atmosphere models were previously used in the X-ray spectral analysis of the *ROSAT* data of V1974 Cyg and atmosphere models convolved with the *ROSAT* response matrix can be found in Balman et al. (1998). The LTE models are expected to be good approximations to the atmospheres of remnant hot WDs *in the X-ray wavelengths*. This follows from Hartmann & Heise (1997) where they show that for  $M_{wd} \geq 0.6 M_{\odot}$  LTE would be established since collisional ionizations dominate (photoionization). The radiation field is more strongly coupled to the local temperature (at high densities) and LTE determines the degree of ionizations and the atomic population levels.

### 3.2 The spectral analysis

The visual magnitude at maximum and early evolution of the visual light curve of GQ Mus was consistent with shell H burning with a metal enrichment about  $Z \sim 0.23$  and helium abundance  $Y \sim 0.4$  (Morisset & Pequignot 1996a). The spectroscopic observations of the source in the nebular phase showed evidence for photoionization from a hot radiation source with temperature  $\sim 4 \times 10^5$  K (35 eV) that increased in time (Krautter & Williams 1989). We reanalyzed the pointed observations of GQ Mus obtained on 1991 August 5-6 (RASS data), 1992 February 25-26, and 1993 January 7-11. The other two following pointed observations on Table 1 were used to derive upper limits on the temperature and flux of the WD because the source was not detected. For the analyses, C-O enhanced WD atmosphere models were used since, the nova was known to be enhanced in CNO nuclei ( $[CNO/Ne-Fe] \sim 38.0$ ) and the  $Ne/Ne_{\odot}$  was low (Livio & Truran 1994; Starrfield et al. 1998).

For the 1992 February observation, the effective temperature of the photosphere was found to lie in the range 38.3-43.3 eV ( $4.4$ - $5.1 \times 10^5$  K) and the unabsorbed X-ray flux (i.e.,  $\sim$  the bolometric flux) was between  $2.5 \times 10^{-9}$  erg s $^{-1}$  cm $^{-2}$  and  $2.3 \times 10^{-10}$  erg s $^{-1}$  cm $^{-2}$  (at  $1\sigma$  confidence level). Figure 1 shows the fitted spectrum of GQ Mus using the atmosphere models that yielded a good fit with  $\chi^2_{\nu} = 1.0$ . The maximum X-ray fluxes were  $1 \times 10^{-8}$  erg s $^{-1}$  cm $^{-2}$  and  $3 \times 10^{-8}$  erg s $^{-1}$  cm $^{-2}$  at  $2\sigma$  and  $3\sigma$  confidence levels, respectively.

The detected bolometric flux and the source distance of  $4.7 \pm 1.5$  kpc yielded a luminosity of about  $(0.3$ - $1.2) \times 10^{37}$  erg s $^{-1}$  for the central source ( $1\sigma$  range with all the uncertainty in the distance taken into account) which is a factor of 10 lower than the constant bolometric



**Figure 1.** The X-ray data fitted with the C-O enhanced WD atmosphere emission models including neutral hydrogen absorption. The smooth curve is the PSPC response to the model spectrum and the actual PSPC data are indicated with crosses. The lower figure shows the residuals between the data and the model in standard deviations.

luminosity of GQ Mus found to be  $\sim 1 \times 10^{38} \text{ erg s}^{-1}$  (Hassel et al. 1990) and  $1.75 \pm 0.3 \times 10^{38} \text{ erg s}^{-1}$  (Morisset & Pequignot 1996b). The constant bolometric luminosities detected for GQ Mus strongly suggest a WD mass  $M_{wd} \geq 0.9 M_{\odot}$  consistent with the large CNO ratio detected for the source as mentioned earlier. In addition, Starrfield et al. (1996), Prialnik & Kovetz (1995), MacDonald et al. (1985) and Morisset & Pequignot (1996b) all imply a WD mass 1.1-1.2  $M_{\odot}$  for GQ Mus. Thus, the choice of the WD mass of 1.2  $M_{\odot}$  in the models used to analyze the ROSAT data is in good agreement with different estimations.

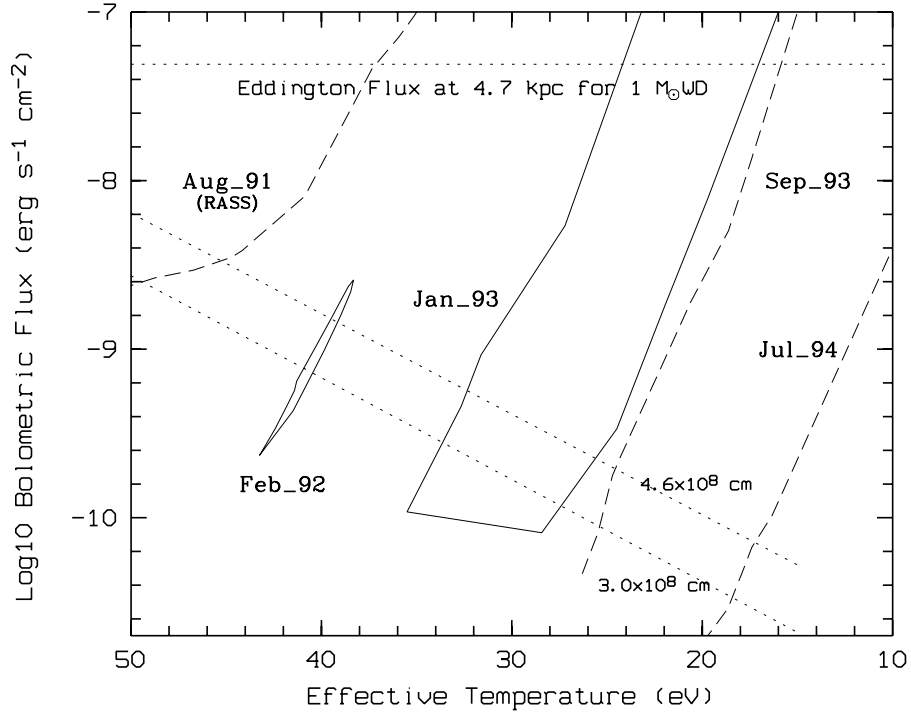
Tuchman & Truran (1998) calculate the core mass-luminosity relation for H burning WDs in classical nova systems as a function of metallicity (i.e.,  $Z$ ). This relation yields a constant bolometric luminosity of  $9.4 \times 10^{37} \text{ erg s}^{-1}$  for a WD of 0.8  $M_{\odot}$ . We derive a  $3\sigma$  maximum limit of  $9 \times 10^{37} \text{ erg s}^{-1}$  for source distances  $d \leq 5 \text{ kpc}$  using our data (Feb 1992). Higher WD mass will increase the constant bolometric luminosity at which the H is burned. As a result, a scenario where H is still burned can be disregarded at  $3\sigma$  confidence level for source distances  $d \leq 5 \text{ kpc}$  (see also Discussion for further details).

We would like to add that the fits showed no significant evidence ( $\leq 2\sigma$ ) for a harder X-ray component above 1 keV that existed in the case of V1974 Cyg (Balman et al. 1998).

The analysis of the 1993 January observation yielded a maximum limit of 35.5 eV ( $4.1 \times 10^5$  K) for the effective temperature of the photosphere and a lower limit of  $8.2 \times 10^{-11}$  erg s $^{-1}$  cm $^{-2}$  for the unabsorbed soft X-ray flux. The unconstrained flux versus effective temperature contour derived from the 1993 January data can be explained by the low count rate which indicates that most of the source spectrum was outside the *ROSAT* energy band. Under such conditions, since the statistical errors are large, the spectral parameters can not be constrained well. The upper limits derived from the 1993 September data on the source temperature and the unabsorbed X-ray flux are 27 eV ( $3.1 \times 10^5$  K) and  $1.1 \times 10^{-10}$  erg s $^{-1}$  cm $^{-2}$ . The upper limits are reduced to 18 eV ( $2.1 \times 10^5$  K) and  $2.2 \times 10^{-11}$  erg s $^{-1}$  cm $^{-2}$  for the 1994 July data (see also Table 2 in sec. [4]).

Since the 1992 data strongly suggests that the source had already turned off, we also obtained the *PSPC* data taken during RASS in 1991 August to determine better H burning and turnoff time-scales. The spectral analysis of the data shows that the effective temperature of the photosphere was  $kT < 54$  eV ( $< 6.2 \times 10^5$  K). The spectral parameters of the RASS data were not constrained well due to the low statistical quality. On the other hand, it shows evidence that the temperature of the WD was higher at fluxes corresponding to the 1992 data. Since the flux was not constrained, it is possible that the WD could be burning H at that time.

In order to examine the spectral development of the remnant WD on an effective temperature versus bolometric flux parameter space (i.e., Hertzsprung-Russell diagram), we prepared confidence contours from our spectral results. We used the generally accepted range of values for the column density of neutral hydrogen,  $N_H \sim (2.0-4.0) \times 10^{21}$  cm $^{-2}$  (Ögelman et al. 1987). Figure 2 represents the relative development of the C-O model parameters in time. The y-axis is the soft X-ray flux from the nova corrected for interstellar  $N_H$ . The distance to the nova does not play any role in the construction of the diagram. The figure shows contours at  $1\sigma$  confidence level, each labelled by the observation date. The horizontal dotted line is the Eddington flux at the distance of the nova (4.7 kpc) for a  $1 M_\odot$  WD. The slanted dotted lines are constant radius paths for the cooling stellar remnant at  $3 \times 10^8$  cm and  $4.6 \times 10^8$  cm. In general, the evolution resembles that of a cooling WD after the H burning ceases.



**Figure 2.** Effective Temperature versus Bolometric Flux. The figure shows five  $1\sigma$  confidence contours derived from the fits with the C-O atmosphere model of emission. Each contour is labelled by the observation date. The two dashed lines on the right hand side show the upper limits for 1993 September and 1994 July data. The dashed line on the left hand side show the maximum flux limit derived from the 1991 August data. The horizontal dotted line is the Eddington flux at the distance of the nova (4.7 kpc) for  $1M_{\odot}$  WD. The slanted dotted lines are the constant radius paths for the cooling stellar remnant calculated using a 4.7 kpc source distance.

#### 4 DISCUSSION AND COMPARISONS

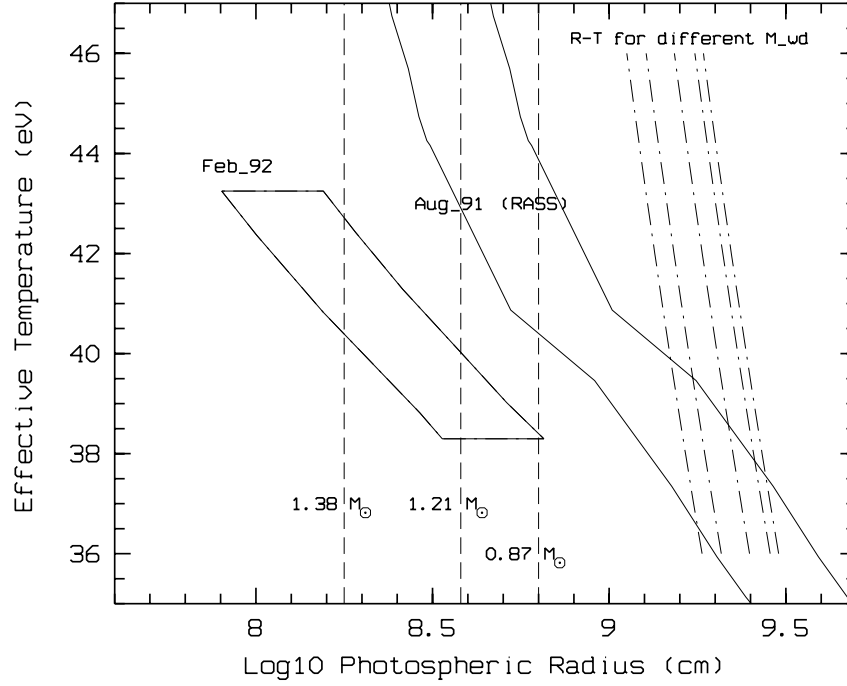
The X-ray spectral analysis showed that most likely GQ Mus had already turned off H burning by the observation in February 1992 (day 3322 after outburst). We found that at  $3\sigma$  confidence level the maximum limit of the X-ray luminosity,  $9 \times 10^{37}$  erg s $^{-1}$  at source distances  $\leq 5$  kpc, is lower than the expected luminosity from a WD ( $M_{WD} \geq 0.8 M_{\odot}$ ) at the constant bolometric luminosity phase of a classical nova evolution. Since the estimated mass of the WD in GQ Mus is  $M_{wd} \geq 0.9 M_{\odot}$  and the calculated distances are more likely around 2-5 kpc (Diaz et al. 1995), the February data is most likely not of a H burning WD, but a cooling one. An earlier data (1991 August, day 3118 after outburst) shows evidence for higher WD effective temperatures ( $< 54$  eV,  $< 6.2 \times 10^5$  K) than derived from the 1992 data. The unconstrained flux values of the 1991 August data (due to low statistical quality) allows the possibility for ongoing H burning. Our spectral results are displayed on Table 2.



The analysis of the optical data of GQ Mus with the photoionization models showed that the source turned off H burning before/around 3296 days after outburst (26 days before the 1992 X-ray data) which is in a good agreement with our results (Morisset & Pequignot 1996b). The turnoff of H burning is also supported by the IUE data taken in 1992 April about 48 days after the X-ray observation (Starrfield et al. 1996). Morisset & Pequignot 1996b further derived that the source temperature after the turnoff was about  $4.1 \pm 0.6 \times 10^5$  K (for day 3296). The temperature range,  $4.4\text{--}5.1 \times 10^5$  K (38.3–43.3 eV), derived in this study for day 3322 after the outburst (1992 February data) is consistent with their results. Overall, there is quite good agreement between our results on the X-ray, uv and the optical spectral analyses.

GQ Mus was observed with the EXOSAT (i.e., 1984) and the ROSAT PSPC (i.e., 1992–1994). The results are summarized in the introduction. The EXOSAT LE did not have energy resolution and the detections were marginal, thus we can not effectively compare the EXOSAT results with our findings. The ROSAT PSPC results *obtained using simple blackbody model of emission* showed a temperature around 30 eV ( $3.5 \times 10^5$  K) for the 1992 February data and a luminosity of  $1 \times 10^{38}$  erg s<sup>−1</sup> consistent with on-going H burning (Ögelman et al. 1993). Shanley et al. (1995) have derived 29–33.5 eV for the range of temperatures and  $1.01\text{--}3.77 \times 10^{-8}$  erg s<sup>−1</sup> cm<sup>−2</sup> for the X-ray flux using the simple blackbody models. The flux and temperature are unconstrained at  $2\sigma$  and  $3\sigma$  confidence levels. The temperature and flux range derived using blackbody model of emission *are not* within our ranges of spectral parameters at  $1\sigma\text{--}3\sigma$  confidence level (see also Table [2]). We like to note that, there is a slight overlap in flux values only at  $3\sigma$  confidence level, but the Eddington values are not allowed (see sec. [3.2]). Assuming that the models used in this paper are the most up-to-date for remnants of classical novae, they are more appropriate for analysis than simple blackbody model of emission for reasons explained in section [3.1]. Shanley et al. 1995 derives a range of 15–29 eV for the WD from the 1993 February data and an upper limit of 21 eV from the 1993 September data *using simple blackbody model of emission*. Our maximum limits and upper limits are higher by 30–20 per cent and we derive an upper limit of 18 eV for the 1994 July data. In general, the blackbody models underestimate the effective temperature and over estimate the X-ray flux for GQ Mus.

In order to investigate more elaborately the turnoff of the nova, we have used the spectral parameters derived using the 1991 August and 1992 February data to construct Figure 3 which shows the contours of acceptable parameters for the effective temperature in eV and



**Figure 3.** Effective Temperature versus Photospheric Radius. The contours show the acceptable parameters for the effective temperature in eV and the photospheric radius in cm at  $1\sigma$  confidence level. All the distance uncertainty is taken into account. The three vertical dashed lines indicate the mass of the WD that has the particular radii (the labels are at the bottom of the lines). The slanted dot-dashed lines on the right hand side show the R-T relationships for  $0.7 M_{\odot}$ ,  $0.8 M_{\odot}$ ,  $1.0 M_{\odot}$ ,  $1.2 M_{\odot}$  and  $1.3 M_{\odot}$  H burning remnant WDs (from left to right).

the photospheric radius in cm. The radii were calculated using the normalization constant  $(R/D)^2$  and *all the distance uncertainty was taken into account*. The vertical dashed lines in the figure indicate the radius of a WD with the labelled mass (of the WD). The calculations were made using the mass-radius tables of Hamada & Salpeter (1961) for a C-O WD. The dot-dashed slanted lines on the right hand side in Figure 3 show the Radius-Temperature relationship for  $0.7 M_{\odot}$ ,  $0.8 M_{\odot}$ ,  $1.0 M_{\odot}$ ,  $1.2 M_{\odot}$  and  $1.3 M_{\odot}$  H burning WDs obtained using the relation of Tuchman & Truran (1998) ( $L/L_{\odot} = 52000(M_{core} - 0.47 + 0.5Z)$ , where  $Z = 0.23$ ). *The  $1.2 M_{\odot}$  curve (dot-dashed line second from left hand side) in Figure 3 overlaps quite well with the calculated R-T relation using our model (MacDonald & Vennes 1991).* The statistical errors of the 1992 February data are such that there is about 78 per cent error in the determination of the photospheric radius in the given range of effective temperatures 38-43 eV. However, the R-T relationships for WDs with different masses (as in the Figure 3) ranging from  $0.8 M_{\odot}$ - $1.3 M_{\odot}$  require statistical errors (of the data in the photospheric

radius) less than 35 per cent so that WD mass can be resolved within  $\Delta M = 0.5 M_{\odot}$ . The required errors are less than 10 per cent to resolve the R-T relationships for WD masses with  $\Delta M = 0.1 M_{\odot}$  (considering the same effective temperature range of 38-43 eV). As a result, though the statistics of the data are not bad, the 1992 February data set and any other ones can not be used to scale the WD mass because it requires quite high signal to noise. In addition, since the model fits the 1992 data well with  $\chi^2_{\nu} = 1.0$ , all the model R-T curves plotted in Figure 3 is expected to be within the error contour of 1992 February data, displayed in Figure 3 if the WD was still burning the H. *For the case of V1974 Cyg most of the R-T curves above  $0.9 M_{\odot}$  were consistent with the data.* In the case of 1991 August data, we have found overlaps between the models and the maximum limit derived from the data. This is an evidence that the WD could have been burning the H at that time. However, we caution that this could also be a manifestation of the low statistical quality of the RASS data. The photospheric radii of V1974 Cyg derived using atmosphere emission models are about a factor of 10 larger than GQ Mus at all times (V1974 Cyg;  $R_{ph} \geq 1.9 \times 10^9$  cm; Balman et al. 1998). The optical spectral analysis using photoionization models shows that the H burning stops between days 2749 and 3296 after the outburst (time span is about 1.5 yrs, Morisset & Pequignot 1996b). The source is found to decrease in luminosity and increase in temperature for the day 3296. Thus, the photosphere shrinks about a factor of 4 using the results of Morisset & Pequignot (1996b) between these dates. If one assumes an effective radius of  $2.2 \times 10^9$  cm for a H burning  $1.2 M_{\odot}$  WD using our model, the expected radius is then  $5.5 \times 10^8$  cm which is in good agreement with our spectral results for the 1992 February data that is about 3322 days after the outburst. This strongly suggests that the photosphere had almost shrunk to its original size and the H burning had already ceased sometime ago. The difference (about a factor of 10) between the photosphere sizes of V1974 Cyg and GQ Mus supports this. In general, if two hot WDs, one H burning and the other not, have the same effective temperature, the difference between the two will be the  $g$  (surface gravity) value. The H burning WD will have a lower  $g$  (thus, larger photospheric radius) compared with a WD which is hot, but not burning hydrogen.

The cooling time-scale of the WD in X-rays can be calculated assuming an exponential decay in temperature at constant radius:  $T = T_o e^{-t/\tau_c}$  where  $\tau_c$  is the cooling time-scale. Using the spectral results derived in section [3.2],  $\tau_c$  is estimated as 3.3 years by fitting the declining temperatures (at constant radius) with an exponential decay in time. Shanley et al. (1995) derived about 3-4 yrs for the cooling time-scale using the blackbody emission models

which is similar to our result. This time scale places the turnoff either in late 1990 or 1991 regardless of the emission model used assuming that the source is not detected (in X-rays) in late 1993 and in the year 1994. This time-scale is also about 3-4 times longer than the 10 months long cooling time-scale detected for V1974 Cyg and it is consistent with the fact that V1974 Cyg is a faster nova than GQ Mus.

The maximum effective temperature for a post-outburst WD can be given by the empirical relation of MacDonald (1996) as  $T_{max} = 6.6 \times 10^5 (M_{wd}/M_{\odot})^{1.6}$  K. The range of effective temperatures derived from the 1992 February data yields a lower limit estimate on the WD mass  $\gtrsim 0.8 M_{\odot}$  since the WD had turned off at that time.

The H burning time-scale (time passed until turnoff) for GQ Mus is less than 8.5 years presuming that it just turned off before/around 1991 August. Over this period, the H-burning rate is predicted to be constant and given by  $\dot{M}_b = L_P/(XE_H)$ . Assuming that  $E_H$  is  $\sim 6.4 \times 10^{18}$  erg gr $^{-1}$  (energy obtained by nuclear conversion of hydrogen to helium),  $X$ , the hydrogen mass fraction, is  $\sim 0.37$  (Morisset & Pequignot 1996a), and  $L_P$  is  $\sim 8.8 \times 10^{38}$  erg s $^{-1}$  (for  $0.8 M_{\odot}$ ; Tuchman & Truran 1998), then the H-burning rate is  $\sim 5.8 \times 10^{-7} M_{\odot}$  yr $^{-1}$ . The detected H-burning time-scale yields a burned envelope mass of  $\sim 5.0 \times 10^{-6} M_{\odot}$ . This value increases to  $9.5 \times 10^{-6} M_{\odot}$  for a  $1.2 M_{\odot}$  WD and thus, corresponds to about < 6-8 per cent of the initial accreted envelope which is  $M_{acc} \sim M_{eject} \sim (1.2 \pm 0.2) \times 10^{-4} M_{\odot}$  (Morisset & Pequignot 1996a). Most of the envelope of the WD must have been driven away by an optically thick wind in the early and/or a radiative wind in the later stages. A very similar result on the burned envelope mass was derived for V1974 Cyg (< 5 per cent; Balman et al. 1998) and this was attributed to the optically thick wind detected as early as 4-5 days after outburst. The observed wind phase derived using the optical data of GQ Mus is  $\leq 0.52$  years (Morisset & Pequignot 1996b). If this is the case only an optically thick wind with a mass loss rate  $\dot{M} > 1 \times 10^{-4} M_{\odot}$  yr $^{-1}$  can account for the burned envelope mass and the H burning time-scale. Such high mass loss rates are consistent with the wind models ( $M_{wd} \geq 1 M_{\odot}$  Kato 1997; Kovetz 1998).

The higher temperatures and smaller radii beyond  $1.38 M_{\odot}$  in Figure 2 translate to an effective emitting region about 2-6 per cent of the whole WD surface (for  $1 M_{\odot}$  WD) which can be interpreted as a hot spot (e.g., as in soft X-ray emitting regions of Am Her-type systems; Gänsicke 1998). The optical and far UV spectra of GQ Mus obtained in years 1989-1994 have also been interpreted as an accreting Am Her-type CV (e.g., double peaked light curve structure in the optical and UV wavelengths; Diaz & Steiner 1994; Diaz et al.

**Table 2.** Spectral Parameters<sup>1</sup> for the Soft X-ray (Photospheric) Components of *ROSAT* Detections of Classical Novae.

Classical Nova	X-ray Obs. Time	kT <sub>eff</sub> (eV) <sup>2</sup>	R <sub>ph</sub> (cm)	F (erg s <sup>-1</sup> cm <sup>2</sup> )	χ <sub>ν</sub> <sup>2</sup>
GQ Mus 1983	8.5 yrs	< 54	> 1.8 × 10 <sup>8</sup>	> 1.3 × 10 <sup>-9</sup>	1.0
	9 yrs	38.3-43.3	(1.8-6.3) × 10 <sup>8</sup>	0.2-2.5 × 10 <sup>-9</sup>	1.0
	10 yrs	< 35.5	> 1.8 × 10 <sup>8</sup>	> 8.2 × 10 <sup>-11</sup>	0.7
	10.6 yrs	< 27	> 1.8 × 10 <sup>8</sup>	< 5.3 × 10 <sup>-11</sup>	1.4
	11.4 yrs	< 18	> 1.8 × 10 <sup>8</sup>	< 2.2 × 10 <sup>-11</sup>	0.5
V838 Her 1991	365 days	< 26	< 3.8 × 10 <sup>9</sup>	< 10 <sup>-8</sup>	1.2
V353 Pup 1991	480 days	< 30	< 3.5 × 10 <sup>9</sup>	< 10 <sup>-8</sup>	1.1

(<sup>1</sup>) ranges and limits are calculated at 1σ confidence level

(<sup>2</sup>) 1eV=1.2 × 10<sup>4</sup>K

1995). Kahabka (1996) shows the existence of about 30 per cent modulation in the light curve of the 1992 February data at the orbital period of GQ Mus which is  $\sim 85.5$  min (Diaz & Steiner 1989). This supports that the suggestion that GQ Mus could be accreting in 1992 February however, the inclination angle of the system is known to be high  $\sim 50^\circ$ - $70^\circ$  (Diaz & Steiner 1994) and thus, occultation by the secondary could easily cause modulations in the X-ray light curve of the nova. The luminosity derived in section [3.2] is not a characteristic of AM Her type CVs (eg.,  $10^{33-34}$  erg s<sup>-1</sup> (Cropper 1990)) and such low luminosities could be disregarded at 3σ confidence level. The X-ray spectral evolution of GQ Mus could be simply explained by a cooling WD after a nova explosion as expected. An elaborate scenario that involves accretion can not be directly inferred from the X-ray observations and thus, is beyond the scope of this paper. The 30 per cent modulation in the light curve can not account for the factor of 10-60 difference between the observed (unabsorbed) flux and the Eddington Flux.

We also applied the metal enhanced model atmospheres to the X-ray data of the other Galactic classical nova detected by the *ROSAT* *PSPC* in order to compare with the results of the analysis of V1974 Cyg and GQ Mus (V838 Her 1991, V351 Pup 1991, and QU Vul 1984; [see Balman 1997 for a review of the analysis]). Table 2 shows the upper limits on the effective temperatures, photospheric radii, and bolometric flux of the other two *ROSAT* detections of Galactic classical novae where we found evidence of soft X-ray emission. An O-Ne enhanced atmosphere model of emission was used for the other three novae consistent with the detected abundance of Ne (Ne/Ne<sub>⊙</sub> > 40). The outburst X-ray spectra of V838 Her, V351 Pup and QU Vul 1984 show only the harder X-ray component with similar characteristic temperature and electron density to V1974 Cyg (Lloyd et al. 1991; Orío et al. 1996; Balman & Ögelman 2000).

The second observation of V838 Her obtained one year later was a marginal detection

( $S/N=7$ ). An effective temperature range of (12.0-26.0) eV ( $1.4-3.0 \times 10^5$  K for  $N_H < 3 \times 10^{21}$  cm $^{-2}$ ) was derived at  $1\sigma$  confidence level which yielded an upper limit of  $3.8 \times 10^9$  cm for the photosphere assuming a WD emitting at the Eddington luminosity ( $\sim 1.7 \times 10^{38}$  erg s $^{-1}$ ). The best-fitting values were an  $N_H$  of  $0.1 \times 10^{21}$  cm $^{-2}$  and an effective temperature of 14.0 eV which yielded an effective radius of  $3.2 \times 10^8$  cm for the photosphere at 5 kpc source distance with an X-ray flux  $\sim 2.5 \times 10^{-10}$  erg s $^{-1}$  cm $^{-2}$ . A Raymond-Smith model of emission (Raymond & Smith 1977) yielded  $\chi^2_\nu$  values larger than 3.0 which supported the photospheric emission interpretation. In order to look for traces of a H burning WD in V351 Pup, we fitted the X-ray spectrum with a two-component model as in V1974 Cyg (see Balman et al. 1998). The second component (Raymond-Smith thermal plasma model) yielded spectral results similar to the single-component fit. Using the O-Ne atmosphere emission models, we derived a range of (25-30) eV ( $3.0-3.5 \times 10^5$  K) at  $1\sigma$  confidence level for the temperature of the alleged stellar remnant ( $1 \times 10^{21} \leq N_H \leq 7 \times 10^{21}$  cm $^{-2}$  at  $3\sigma$  confidence level). This indicated that the soft X-ray source could be a cooling WD with an upper limit on the effective radius  $\leq 3.5 \times 10^9$  cm using the temperature estimate above and the Eddington luminosity ( $\sim 1.7 \times 10^{38}$  erg s $^{-1}$ ). Orio et al. (1996) have also calculated a similar temperature of (17.0-25.0) eV ( $2.0-3.0 \times 10^5$  K) for the central source using strong [Ne III] lines in the optical spectra.

The few examples discussed in this paper indicate that the soft X-ray components (0.1-10 keV) of classical novae were not detected with the *ROSAT* satellite once the temperature of the stellar remnant was  $< 30$  eV. It is highly likely that for the case of V838 Her and V353 Pup the soft component had already subsided at the time of the X-ray observations. Besides these, Nova LMC 1995 has been detected by *ROSAT* *PSPC* as a third soft X-ray source (kT $<38$  eV) three years after its outburst in 1998 (Orio & Greiner 1999). In addition, the recurrent nova U Sco is detected as a H burning WD (kT $\sim 77.5$  eV) in its recent outburst (Kahabka et al. 1999). Both detections are single observations in time and an evolutionary scenario can not be drawn.

## 5 CONCLUSIONS

The spectral analysis of the soft X-ray data of GQ Mus (0.1-1 keV) show significant differences from the results obtained using a blackbody model of emission. The use of metal enhanced atmosphere emission models instead of a blackbody model of emission to study

the soft X-rays from hot WDs is proved once again to be of great importance. We find that the source had most likely ceased H burning prior to February 1992 and was in the cooling stage at the time of the X-ray observations indicating that the H burning time-scale is  $< 8.5$  yrs. This is also consistent with the data in the optical and uv wavelengths. This study also stresses the distinction between a super soft X-ray source and a H-burning WD as that the former does not imply the latter. The data obtained in 1991 August yields only a maximum limit on temperature as 54 eV ( $\sim 6.2 \times 10^5$  K) which indicates that the source was more hot in 1991 compared to 1992, supporting the standard nova theory that implies massive WDs in classical nova systems. We derive a temperature range of 38.3-43.3 eV ( $4.4$ - $5.1 \times 10^5$  K) for the central source together with an unabsorbed X-ray flux ( $\sim$  bolometric flux) of  $(2.5$ - $0.23) \times 10^{-9}$  erg s $^{-1}$  cm $^{-2}$  for the 1992 February data. All the results are displayed in Table 2. The lower limit on the mass of the WD is estimated as  $M_{wd} \gtrsim 0.8 M_{\odot}$ . We obtained 3.3 yrs for the cooling time-scale of the classical nova and the source was not detected in the 1994 July 6 observation as was in the 1993 September 3 observation (consistent with this time-scale). We calculated that the burned envelope mass is less than 6-8 per cent of the accreted envelope which suggests that most of the material was ejected in a wind with  $\dot{M} > 1 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$  at the earlier phases of the outburst. We have not detected a secondary hard component (1-10 keV) expected as a result of a wind-wind/circumstellar interaction of the ejected material. However, we suggest that the cooling time-scale of such a component could be less than 10 yrs since the wind phase was only 0.5 yrs. GQ Mus is a standing proof (after V1974 Cyg) of the predictions of the standard nova theory where one expects a hot luminous central star increasing in temperature as the H in the envelope is burned and cooling at constant radius after the turnoff. There have been few detections of soft X-ray components of classical novae due to several reasons: 1) Since most novae have been observed in X-rays only once, it is difficult to predict any evolutionary scenario and detect the existence of a H burning hot WD. 2) The length of H burning time scale could be short (i.e., massive WDs) and the sources could be turned off before the X-ray observation (ie., V838 Her second obs. and V351 Pup). 3) The intrinsic  $N_H$  in the shell could be too high at the time of the X-ray observations and most of the soft X-rays could be absorbed (early phases of V1974 Cyg). Therefore, monitored target of opportunity observations of classical novae in X-rays is probably the only way useful information can be obtained and used as probes in understanding the nova explosions and standard nova theory (as it was done for

V1974 Cyg [Krautter et al. 1996; Balman et al. 1998] and Nova Vel 1999 [Orio et al. 1999; Mukai & Ishida 1999]).

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